Diagnostic System for Venturi Meters

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1. Introduction

Venturi flow meters are popular for being simple, sturdy, reliable and inexpensive devices. Their principles of operation are easily understood. However, traditionally there has been no Venturi meter self diagnostic capabilities. In 2008 and 2009 a generic DP meter self diagnostic methodology [1,2,3] was proposed. In this paper these DP meter diagnostic principles are discussed specifically with respect to Venturi meters. In this paper the principles are proven with extensive experimental test results from Venturi meters. A diagnostics screen displaying the diagnostic results real time, first suggested in 2009 [2, 3], is discussed and then used to present the experimental results.

2. The Venturi meter self diagnostic principles

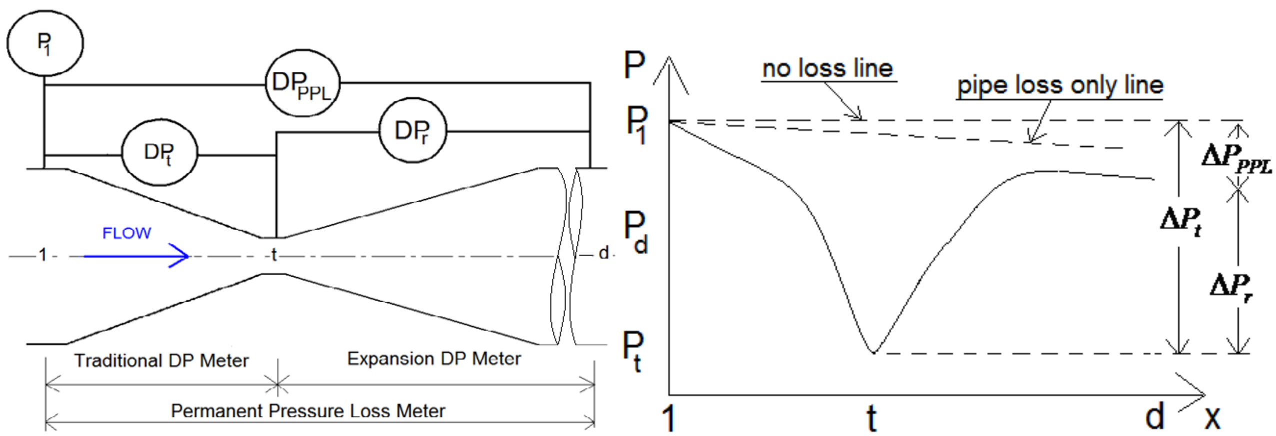

Fig 1. Venturi meter with instrumentation sketch and pressure fluctuation graph

Figure 1 shows a Venturi meter with instrumentation sketch and the (simplified) pressure fluctuation through the meter body. Traditional Venturi meters read the inlet pressure (P_1), the downstream temperature (T) and the differential pressure (ΔP_t) between the inlet pressure tap (1) and a pressure tap positioned at the throat, i.e. the point of low pressure (t). Note that the Venturi meter in Figure 1 has a third pressure tap (d) downstream of the diffuser. This addition to the traditional Venturi meter design allows the measurement of two extra DP's. That is, the differential pressure between the downstream (d) and the low (t) pressure taps (or "recovered" DP, ΔP_r) and the differential pressure between the inlet (1) and the downstream (d) pressure taps (i.e. the permanent pressure loss, ΔP_{PPL}, sometimes called the "PPL" or "total head loss").

The sum of the recovered DP and the PPL equals the traditional differential pressure (equation 1). Hence, in order to obtain three DP's, only two DP transmitters are required.

$$\Delta P_t = \Delta P_r + \Delta P_{PPL} \quad \text{--- (1)}$$

Traditional Flow Equation: $\dot{m}_t = EA_t YC_d \sqrt{2\rho\Delta P_t}$, uncertainty ± x% --- (2)

Expansion Flow Equation: $\dot{m}_r = EA_t K_r \sqrt{2\rho\Delta P_r}$, uncertainty ± y% --- (3)

PPL Flow Equation: $\dot{m}_{ppl} = AK_{PPL} \sqrt{2\rho\Delta P_{PPL}}$, uncertainty ±z% --- (4)

The traditional Venturi meter flow rate equation is shown here as equation 2. Traditionally, this is the only Venturi meter flow rate calculation. However, with the additional downstream pressure tap three flow equations can be produced. That is, the recovered DP can be used to find the flow rate with an “expansion” flow equation (see equation 3) and the PPL can be used to find the flow rate with a “PPL” flow equation (see equation 4). Note $\dot{m}_t$, $\dot{m}_r$ and $\dot{m}_{PPL}$ represents the traditional, expansion and PPL mass flow rate equation predictions of the actual mass flow rate ($\dot{m}$) respectively. The symbol ρ represents the fluid density. Symbols E , A and A_t represent the velocity of approach (a constant for a set meter geometry), the inlet cross sectional area and the minimum (or “throat”) cross sectional area through the meter respectively. Y is an expansion factor accounting for gas density fluctuation through the meter. (For liquids Y =1.) The terms C_d , K_r and K_{PPL} represent the discharge coefficient, the expansion coefficient and the PPL coefficient respectively. These are found by calibrating the Venturi meter and each can be set as constant values with set uncertainty ratings, or, may each be fitted to the Reynolds number, usually at a lower uncertainty rating. The Reynolds number is expressed as equation 5. Note that μ is the fluid viscosity and D is the inlet diameter. In this case, as the Reynolds number (Re) is flow rate dependent, each of the three flow rate predictions must be independently obtained by an iterative method within a flow computer. A detailed derivation of these three flow rate equations is given by Steven [1].

$$\mathrm{Re} = \frac{4\dot{m}}{\pi\mu D} \quad \text{--- (5)}$$

Every Venturi meter body is in effect three flow meters. As there are three flow rate equations predicting the same flow through the same meter body there is the potential to compare the flow rate predictions and hence have a diagnostic system. Naturally, all three flow rate equations have individual uncertainty ratings (say x%, y% & z% as shown in equations 2 through 4). Therefore, even if a DP meter is operating correctly, no two flow predictions would match *precisely*. However, a correctly operating meter should have no difference between any two flow equations greater than the sum of the two uncertainties. The calibration therefore produces three more values, i.e. the maximum allowable difference between any two flow rate equations, i.e. $\phi\%$, $\xi\%$ & $\upsilon\%$ as shown in equation set 6a to 6c. This allows a self diagnosing system. If the percentage difference between any two flow rate equations is less than that equation pairs summed uncertainties (found from the meters calibration), then no potential problem is found and the traditional flow rate prediction can be trusted. If however, the percentage difference between any two flow rate equations is greater than that equation pairs summed uncertainties then this indicates a metering problem and the flow rate predictions should not be trusted. The three flow rate percentage differences are calculated by equations 7a to 7c:

Traditional & PPL Meters % allowable difference (ϕ %): $\phi\% = x\% + z\%$ -- (6a)

Traditional & Expansion Meters % allowable difference (ξ %): $\xi\% = x\% + y\%$ -- (6b)

Expansion & PPL Meters % allowable difference (υ %): $\upsilon\% = y\% + z\%$ -- (6c)

Traditional to PPL Meter Comparison : $\psi\ \% = \left\{ \left(\dot{m}_{PPL} - \dot{m}_t \right) \Big/ \dot{m}_t \right\} *100\%$ -- (7a)

Traditional to Expansion Meter Comparison: $\lambda\ \% = \left\{ \left(\dot{m}_r - \dot{m}_t \right) \Big/ \dot{m}_t \right\} *100\%$ -- (7b)

PPL to Expansion Meter Comparison: $\chi\ \% = \left\{ \left(\dot{m}_r - \dot{m}_{PPL} \right) \Big/ \dot{m}_{PPL} \right\} *100\%$ -- (7c)

This diagnostic methodology uses the three individual DP's to independently predict the flow rate and then compares these results. In effect, the individual DP's are therefore being directly compared. However, it is possible to take a different diagnostic approach. The **P**ressure **L**oss **R**atio (or "PLR") is the ratio of the PPL to the traditional DP. <u>The PLR is some particular constant for each Venturi meter operating with single phase homogenous flow</u>. We can rewrite Equation 1:

$$\frac{\Delta P_r}{\Delta P_t} + \frac{\Delta P_{PPL}}{\Delta P_t} = 1 \quad \text{--- (1a)} \qquad \text{where} \qquad \frac{\Delta P_{PPL}}{\Delta P_t} \text{ is the PLR.}$$

From equation 1a, if PLR is a constant set value then both the **P**ressure **R**ecovery **R**atio or "PRR", (i.e. the ratio of the recovered DP to traditional DP) and the **R**ecovered DP to **P**PL **R**atio, or "RPR" must then also be constant set values. That is, all DP ratios available from the three DP pairs are constant values for any given DP meter geometry and can be found by the *same* calibration that finds the three flow coefficients. Thus we also have:

PPL to Traditional DP ratio (PLR): $\left(\Delta P_{PPL} / \Delta P_t \right)_{cal}$, uncertainty ± a%

Recovered to Traditional DP ratio (PRR): $\left(\Delta P_r / \Delta P_t \right)_{cal}$, uncertainty ± b%

Recovered to PPL DP ratio (RPR): $\left(\Delta P_r / \Delta P_{PPL} \right)_{cal}$, uncertainty ± c%

Here then is another method of using the three DP's to check a DP meters health. Actual DP ratios found in service can be compared to the calibrated values. Let us denote the difference between the actual PLR and the calibrated value as α, the difference between the actual PRR and the calibrated value as γ, and the difference between the actual RPR and the calibrated value as η. These values are found by equations 8a to 8c.

$$\alpha\ \% = \left\{ \left[PLR_{actual} - PLR_{calibration} \right] / PLR_{calibration} \right\} *100\% \quad \text{--- (8a)}$$

$$\gamma\ \% = \left\{ \left[PRR_{actual} - PRR_{calibration} \right] / PRR_{calibration} \right\} *100\% \quad \text{--- (8b)}$$

$$\eta\ \% = \left\{ \left[RPR_{actual} - RPR_{calibration} \right] / RPR_{calibration} \right\} *100\% \quad \text{--- (8c)}$$

<u>The standard calibration of a Venturi meter with a downstream pressure tap can produce six meter parameters with nine associated uncertainties.</u> These six parameters are the discharge coefficient, expansion flow coefficient, PPL coefficient, PLR, PRR and RPR. The nine uncertainties are the six parameter uncertainties (±x%, ±y%, ±z%, ±a%, ±b% & ±c%) and the three flow rate inter-comparison uncertainties ($\pm\psi$ %, $\pm\lambda$, $\pm\chi$ %). ***These fifteen Venturi meter parameters found by a standard calibration define the Venturi meters correct operating mode***. Any deviation from this mode beyond the acceptable uncertainty limits is an indicator that there is a meter malfunction and the traditional meter output is therefore not trustworthy. Table 1 shows the six possible situations that should signal an alarm. Note that each of the six diagnostic checks has ***normalized data***, i.e. each meter diagnostic parameter output is divided by the allowable difference for that parameter.

DP Pair	No Alarm	ALARM	No Alarm	ALARM
ΔP_t & ΔP_{ppl}	$\psi\%/\ \phi\% \le 1$	$\psi\%/\ \phi\% > 1$	$\alpha\% \ /\ a\% \le 1$	$\alpha\% \ /\ a\% > 1$
ΔP_t & ΔP_r	$\lambda\%/\ \xi\% \le 1$	$\lambda\%/\ \xi\% > 1$	$\gamma\% \ /\ b\% \le 1$	$\gamma\% \ /\ b\% > 1$
ΔP_r & ΔP_{ppl}	$\chi\%/\ \upsilon\% \le 1$	$\chi\%/\ \upsilon\% > 1$	$\eta\% \ /\ c\% \le 1$	$\eta\% \ /\ c\% > 1$

Table 1. The Venturi meter possible diagnostic results.

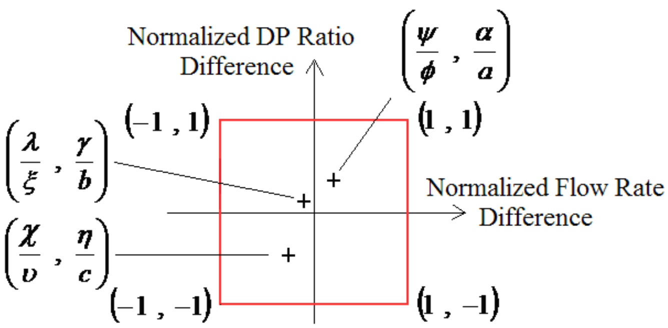

Fig 2. A normalized diagnostic calibration box with normalized diagnostic result.

For practical real time use, a graphical representation of the diagnostics continually updated on a control room screen can be simple and effective. Any such graphical representation of diagnostic results should be immediately accessible and understandable to the user. Therefore, DP Diagnostics proposed that the three points be plotted on a normalized graph (as shown in Fig 2). This graphs abscissa is the normalized flow rate difference and the ordinate is the normalized DP ratio difference. These normalized values have no units. On this graph a normalized diagnostic box (or "NDB") can be superimposed with corner co-ordinates: (1, 1), (1,−1), (−1,−1) & (−1,1). On such a graph three meter diagnostic points can be plotted, i.e. $(\psi/\phi, \alpha/a)$, $(\lambda/\xi, \gamma/b)$ & $(\chi/\upsilon, \eta/c)$. That is, the three DP's have been split into three DP pairs and for each pair both the difference in the flow rate predictions and the difference in the actual to calibrated DP ratio are being compared to the calibrations maximum allowable differences. If all points are within the NDB the meter operator sees no metering problem and the traditional meters flow rate prediction should be trusted. However, if one or more of the three points falls outside the NDB the meter operator has a visual indication that the meter is ***not*** operating correctly and that the meters traditional (or any) flow rate prediction cannot be trusted. The further from the NDB the points are, the more potential for significant meter error there is. Note that in this random theoretical example shown in Figure 2 all points are within the NDB indicating the meter is operating within the limits of normality, i.e. no metering problem is noted.

3. <u>The Necessity to Flow Calibrate Venturi Meters</u>

This description of the diagnostic methodology clearly indicates that six parameters and their associated uncertainties are required for the diagnostic system to operate. These parameters are the discharge coefficient, the expansion flow coefficient, the PPL coefficient, PLR, PRR and the RPR. If the discharge coefficient and PLR are accurately known it is technically possible to derive the other four parameters from this information. Predictions for a Venturi meters PLR are given in the literature (e.g. Miller [4]) but no associated uncertainty ratings are given, so these predictions should only be used for approximate hydraulic pipe loss calculations, not precision diagnostic methodologies. Predictions for Venturi meter discharge coefficients over set flow condition ranges are given by ISO 5167 Part 4 [5]. However, although many in industry tend to use these predictions for all Venturi meter applications, the flow condition ranges covered by this standard are actually rather limited. That is, it should be noted that ISO 5167 [5] is <u>only</u> valid over set ranges of Venturi meter geometries and flow conditions. For example, ISO 5167 includes a discussion on the high precision machined convergent section Venturi meter. This is Venturi meter type primarily used in natural gas flow production. The limits of this meters ISO performance declaration are:

$$50 \text{ mm } (2") \le D \le 250 \text{ mm } (10")$$
$$0.4 \le \beta \le 0.75$$
$$2e5 \le \text{Inlet Reynolds Number } (D) \le 1e6$$

Many industrial natural gas flow conditions have meter sizes and application flow conditions out with these limits of the ISO Venturi meter standard. Extrapolating the ISO discharge coefficient prediction to other conditions is a relatively common practice but it is not valid. ISO 5167 states that as long as the Venturi meter is within the geometry and flow condition range discussed the discharge coefficient is a constant, i.e. $C_d = 0.995$ to an uncertainty of ±1%. However, ISO 5167 also states:

"Research into the use of Venturi tubes in high-pressure gas [$\ge$ 1 MPa ($\ge$ 10 bar)] is being carried out at present. In many cases for Venturi tubes with machined convergent sections discharge coefficients which lie outside the range predicted by this part of ISO 5167 by 2% or more have been found. <u>For optimum accuracy Venturi tubes for use in gas should be calibrated over the required flow rate range</u>."

Furthermore, ISO also explain that a simultaneous use of the limits extreme values of D, β, Re(D) shall be avoided as otherwise the Venturi meter flow rate uncertainty is likely to increase. They therefore state that for <u>installations outside these diameter, beta ratio, pressure and Reynolds number limits, it remains necessary to calibrate the meter in its actual conditions of service</u>.

Many industrial applications have pressures greater than 10 bar (abs) and Reynolds numbers greater than 1e6 and many applications have pipe diameters greater than 10". ***Therefore, in many actual applications the ISO Venturi meter standard is inapplicable.*** In such cases the discharge coefficient must be found by calibration across the range of flow conditions for which the meter will be used.

Figure 3 shows a reproduction of massed Venturi meter gas flow calibration results shown by Geach [6] in 2005. Note that the size range was a diameter range of 6" to 10" and a beta ratio range of 0.48 to 0.7. Hence, all these meters were within the geometry range of the ISO Venturi meter discharge coefficient prediction. However, the data sets were for pipe Reynolds numbers greater than one million, i.e. higher than the upper limit of the ISO range. Superimposed on the graph is the ISO

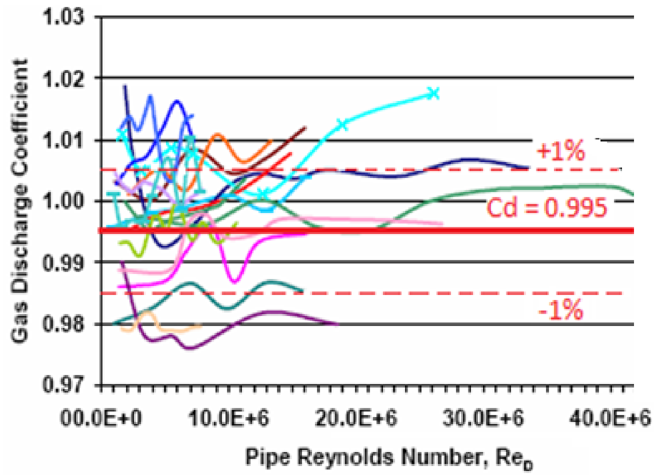

Fig 3. Eighteen ConocoPhillips Venturi meter data sets.

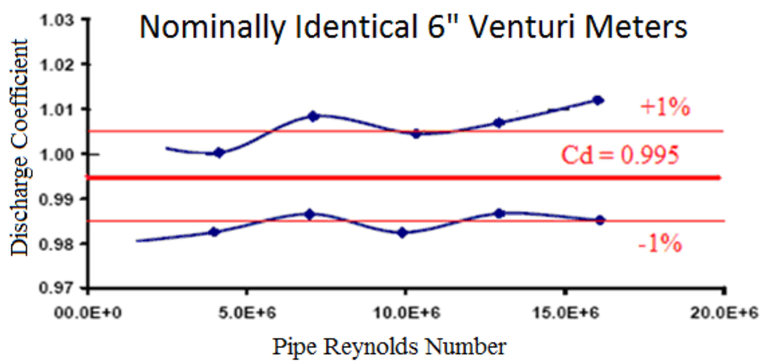

Fig 4. Nominally identical 6" ISO compliant Venturi meters compared to each other.

discharge coefficient prediction for these Venturi meters extrapolated to the higher Reynolds numbers conditions. Clearly many of the meters do not have performances that matched the extrapolated ISO discharge coefficient predictions.

It has also been noted that nominally identical Venturi meters built by the same manufacturer to the same drawing, to the same machining tolerance with the same fabrication equipment can have different performances. Figure 4 show the result of two such Venturi meters being calibrated. The meters were stated to be ISO compliant 6" Venturi meters but the beta ratio was not disclosed. There is approximately a 2% difference in the discharge coefficient between the meters. As the ISO discharge coefficient prediction is often simply extrapolated this is shown in the Figure. For one meter the extrapolated ISO prediction is approximately 1% low and for the other it is 1% high, with some points exceeding the users expected 1% uncertainty limit. The blind application of extrapolated ISO stated discharge coefficient predictions can lead to flow measurement errors. Therefore, for low flow rate uncertainty, Venturi meters with flow conditions outside the ISO scope should be individually calibrated across the full Reynolds number range of the meters application.

If for many industrial flow metering applications it is necessary to calibrate each Venturi meter anyway, it is little more trouble to add an extra pressure tapping downstream and calibrate the meter for all the diagnostic parameters. The system could have three DP transmitters attached to read each of the three DP's individually for the lowest uncertainty in performance. Otherwise, for a small increase in the recovered DP uncertainty the system could have just two DP's read, i.e. the traditional DP and PPL readings, and the recovered DP derived from equation 1. This is what was done in the following testing of a diagnostic capable Venturi meter.

4. A CEESI Calibration of a 4", schedule 80, 0.6 Beta Ratio Venturi Meter

Figure 5 shows a 4", schedule 80, 0.6 beta ratio Venturi meter installed at the CEESI natural gas flow loop. Note that the Venturi meter has an extra pressure tap on the downstream spool. The traditional DP and the PPL were read during the gas flow test. The recovered DP could therefore be found by equation 1. Note that the downstream pressure port is located six diameters downstream of the Venturi meter exit as this is the distance suggested by ISO [5] to assure maximum pressure recovery. However, in some field applications 6D of downstream length may not be available. In this case it is possible to shorten this length. This is not ideal as the downstream pressure tap may not be at a location where full recovery has taken place. However, as long as the system is calibrated in this configuration the resulting information allows the diagnostic system to operate. This was indicated in 2008 by Steven [1] with use of sample Venturi meter data.

Fig 5. 4", 0.6 beta ratio Venturi meter installed in the CEESI wet natural gas loop.

The Venturi meter shown under test at CEESI in Figure 5 was actually being prepared for wet natural gas flow testing. However, before this commenced a dry gas baseline was recorded. In effect the meter was first calibrated for single phase flow. The resulting gas flow data allows us to investigate the diagnostic principles discussed above. The wet natural gas loop at CEESI is not a single phase gas flow calibration facility. It is designed to be a wet natural gas loop facility. Therefore, the gas flow rate reference meter here had higher uncertainty than for CEESI gas calibration facilities. The reference gas flow metering system was a 6" gas turbine with a gas chromatograph. The resulting reference mass flow rate was 0.75%. This reference flow rate data was used to fully calibrate the Venturi meter under test. Figures 6 & 7 show the resultant full calibration.

Table 1 shows this calibration data set. For the wet gas flow tests only one dry gas baseline pressure / gas density was required, so the data set presented here is for 45 kg/m^3. However, the lack of different gas density data sets is of little consequence as there was no need for multiple pressure

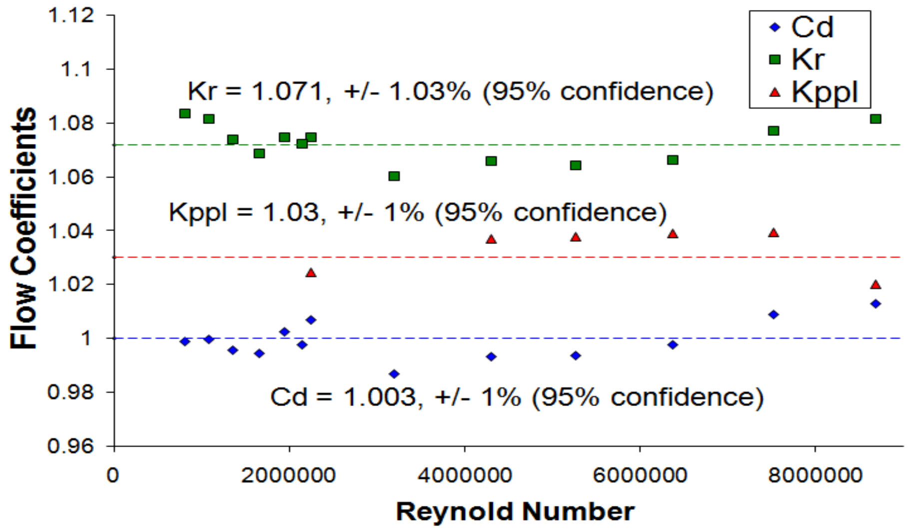

Figure 6. CEESI calibrated 4”, sch 80, 0.6 beta ratio Venturi meter flow coefficients.

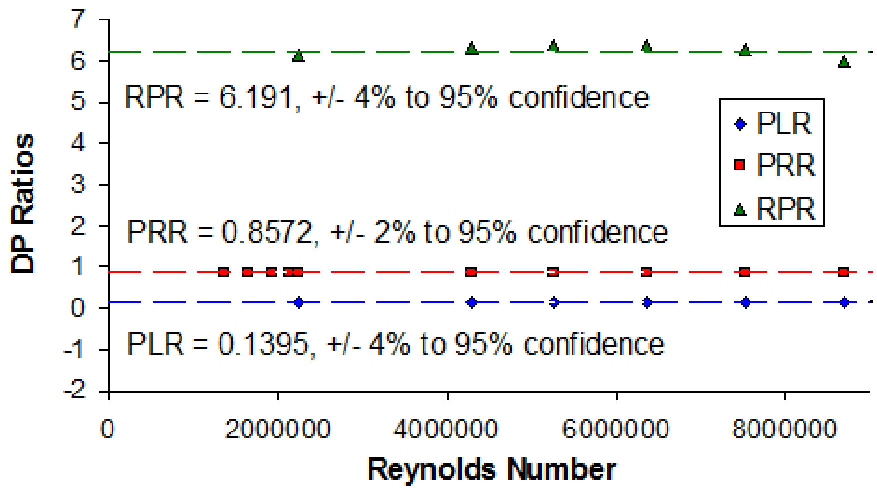

Figure 7 CEESI calibrated 4”, schedule 80, 0.6 beta ratio Venturi meter DP ratios.

Reynolds Number	Discharge Coefficient	Expansion Coefficient	PPL Coefficient	Pressure Loss Ratio	Pressure Recovery Ratio	Recovered to PPL Ratio
	Cd	Kr	Kppl	PLR	PRR	RPR
1082528	1.000	1.081	PPL < 10"	N/A	0.850	N/A
1357418	0.996	1.074	PPL < 10"	N/A	0.853	N/A
1654763	0.994	1.068	PPL < 10"	N/A	0.856	N/A
1936219	1.003	1.075	PPL < 10"	N/A	0.856	N/A
2142522	0.998	1.072	PPL < 10"	N/A	0.864	N/A
2250269	1.007	1.074	1.024	0.141	0.859	6.099
4299846	0.993	1.066	1.037	0.136	0.864	6.356
5268323	0.994	1.064	1.038	0.136	0.864	6.380
6369185	0.998	1.066	1.039	0.136	0.864	6.372
7520315	1.009	1.077	1.039	0.138	0.862	6.248
8679434	1.013	1.082	1.020	0.144	0.856	5.967
All points taken at 45 kg/m3 +/- 1%						

Table 1. CEESI natural gas calibration data of a 4”, 0.6 beta ratio Venturi meter.

tests. It is known that none of the six diagnostic parameters are pressure / fluid density dependent. This was clearly shown to be the case for all generic DP meters in 2008 by Steven [1]. Some of the data points had PPL values less than 10 inches Water Column ("WC). As this was low for the 125"WC spanned transmitter used to read the PPL, only DP data greater than 10"WC was used. This is the simple reason why in Figures 6 & 7 and Table 1 certain data sets have more results shown than others. Figure 6 shows the calibration of three flow coefficients for the three Venturi meter flow rate equations (i.e. equation 2 to 4). Note that the Reynolds range has even a minimum Reynolds number value well in excess of the ISO [5] maximum allowed Reynolds number value for the ISO discharge prediction to be valid. The resulting necessary calibration shows that all three methods of flow rate prediction (i.e. equation 2 thru 4) are practically useful and not just an academic concept. Likewise, Figure 7 shows the three DP ratio values. The scatter ranges around the averaged baseline values of the three DP ratios is seen to be between 2% and 4% thus proving that the DP ratios are relatively constant on a correctly working flow meter across various flow rates. Figure 8 shows the summarized results of the CEESI Venturi meter full calibration. Note the boxes indicating the standard DP meter calibration output. This usually consists of discharge coefficient information and an associated uncertainty. On very rare occasions a PLR is also recorded during meter calibration but this is solely for the use of hydraulic loss predictions across the over all pipe system in which the meter will be installed. An associated uncertainty to the PLR is virtually never requested and this information is never used for any form of Venturi meter diagnostics.

4", 0.6 beta ratio Venturi meter

$$\boxed{C_d = 1.003 \quad x = 1\%} \qquad \phi\% = x\% + z\% = 2\%$$

$$K_r = 1.071 \quad y = 1.03\% \qquad \xi\% = x\% + y\% = 2.03\%$$

$$K_{PPL} = 1.03 \quad z = 1\% \qquad \upsilon\% = y\% + z\% = 2\%$$

$$\boxed{PLR = 0.1395} \qquad a = 4\%$$

$$PRR = 0.8572 \qquad b = 2\%$$

$$RPR = 6.191 \qquad c = 4\%$$

Figure 8. Summary of CEESI Venturi meter full calibration results.

Figure 8 shows that although there are traditionally only two parameters to a standard Venturi meter calibration output (i.e. the discharge coefficient and its uncertainty) with the simple addition of any extra single DP meter transmitter the same calibration procedure can produce, for virtually the same effort and cost, fifteen parameters. That is, an addition of a single extra DP transmitter to a Venturi meter can return multiple times the information than a standard calibration on that meters flow characteristics. This wealth of extra information allows the Venturi meter system a considerable amount of diagnostic capability.

Figure 9 shows this calibrated meters diagnostic points plotted with a NDB as described in section 2. Note all the calibration data is inside the NDB indicating that the meter is operating correctly. This is in itself a trivial result. The uncertainties of the six parameters were set by the very calibration data now plotted on the graph so by consequence all resulting calibration data ***must*** be inside the NDB. However, once a full calibration has allowed all the Venturi meters characteristics to be known as shown in Figure 8, it is possible to set up such a NDB plot to monitor the meters performance in its application, i.e. once there is no reference meter available. Traditionally in this situation there are no diagnostic methods available for Venturi meters. However, using this described method gives the meter simple but very effective diagnostics.

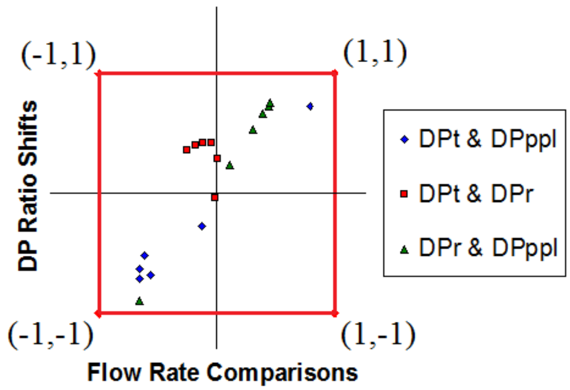

Figure 9. The 4”, 0.6 beta ratio Venturi meter calibration data plotted with a NDB.

The following section shows the response of the Venturi meter diagnostics when various common real world issues cause the meter to give an incorrect flow rate prediction. The examples given are incorrect inlet diameters used, incorrect throat diameters used, an incorrect discharge coefficient input, a saturated DP transmitter and wet gas flow.

5. <u>Examples of Incorrect Operation of Venturi Meters and the Diagnostic Response</u>

Traditionally, the Venturi meter would have no self-diagnostics to check its performance. The only way to check the Venturi meters flow rate prediction, other than costly scheduled maintenance, would be to carry out a system mass balance check. This is time consuming, imprecise and if this check results in a problem being suspected it is not clear if a flow meter is the problem, and even if it was it is not clear which meter in the overall system has the problem. Self diagnostics for Venturi meters are therefore very desirable to industry.

5.1. <u>Incorrect Input of Inlet Diameter</u>

Modern Venturi meters operate with flow computers. The flow computer must be told the inlet and throat diameter of the meter. A common error in Venturi meter operation is therefore to input the wrong inlet diameter. This Venturi meter has an actual inlet diameter (D) of 3.826”. When this value is used with the calibration data the calibrated meter gives the correct gas flow rate to within the stated 1% uncertainty. However, if a wrong value is given to the calculation an error in the traditional meters flow rate prediction occurs. Here we consider a typing mistake where the entered inlet diameter is too small at 3.686” instead of 3.826”. This creates a positive bias of approximately 2% on the flow meters flow rate prediction. Whereas a correctly operating meter will give the flow rate prediction in a range of +1% to -1% this incorrect diameter has shifted this range to +3% to +1%. This is shown in Figure 10. Figure 11 shows the diagnostic result.

Clearly, the diagnostics pick up that the meter flow rate prediction error. Next we consider a mistake where the entered inlet diameter is 4.09”(i.e. schedule 40) instead of 3.826” (i.e. schedule 80). This positive inlet diameter error induces a negative bias of approximately 2% on the flow meters flow rate prediction. Whereas a correctly operating meter will give the flow rate prediction in a range of +1% to -1% this incorrect diameter has shifted this range to -1% to -3%. This is shown in Figure 10.

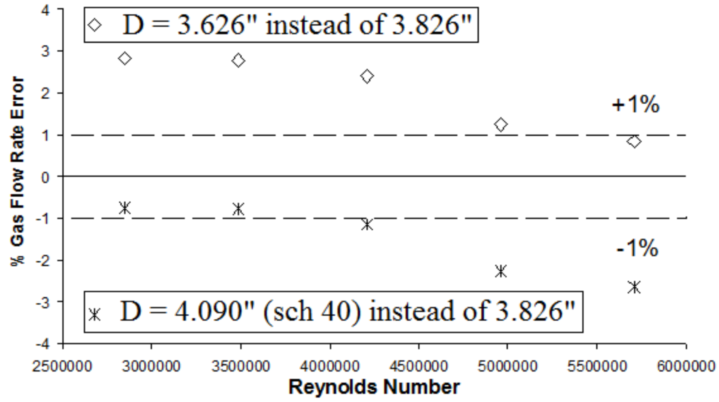

Figure 10. Venturi meter errors associated with incorrect inlet diameter inputs.

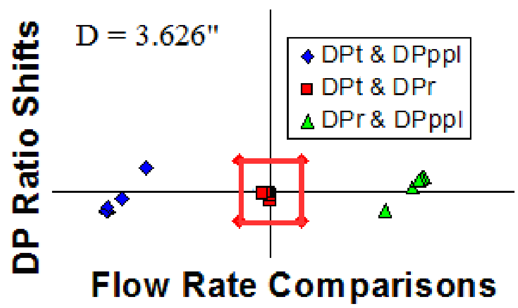

Figure 11. Negative inlet diameter error producing a positive flow rate prediction error.

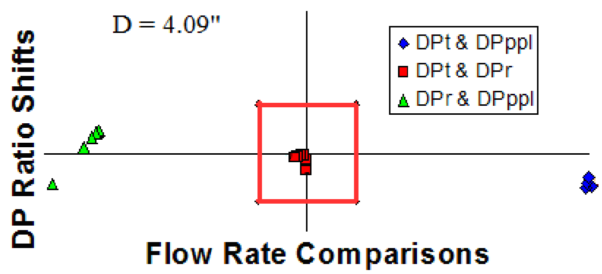

Figure 12. Positive inlet diameter error producing a negative flow rate prediction error.

Figure 12 shows the diagnostic result. Clearly, the diagnostics pick up that the meter flow rate prediction error. Note that the positive and negative errors in the inlet diameters produce negative and positive flow rate prediction errors respectively. The patterns on the NDB plots are likewise opposite.

5.2. <u>**Incorrect Inputs of Throat Diameters**</u>

Another common Venturi meter flow computer input error is to give the wrong throat diameter. This Venturi meter has an actual throat diameter (d) of 2.296". When this value is used with the calibration data the calibrated meter gives the correct gas flow rate to within the stated 1% uncertainty. However, if a wrong value is given to the calculation an error in the traditional meters flow rate prediction occurs. The first example considers too large a throat diameter at 2.35" instead of 2.296". This creates a positive bias on the flow meters flow rate prediction of approximately 5%. Whereas a correctly operating meter will give the flow rate prediction in a range of +1% to -1% this incorrect throat diameter has shifted this range to +6% to +4%. This is shown in Figure 13. Figure 14 shows the diagnostic result. The diagnostics pick up that the meter flow rate prediction error. Next we consider too small a throat diameter of 2.25” instead of 2.926”. This negative inlet diameter error induces a negative bias on the flow meters flow rate prediction of approximately 5%. Whereas a correctly operating meter will give the flow rate prediction in a range of +1% to -1% this incorrect throat diameter has shifted this range to -4% to -6%. This is also shown in Figure 13. Figure 15 shows the diagnostic result. The diagnostics pick up that the meter flow rate prediction error.

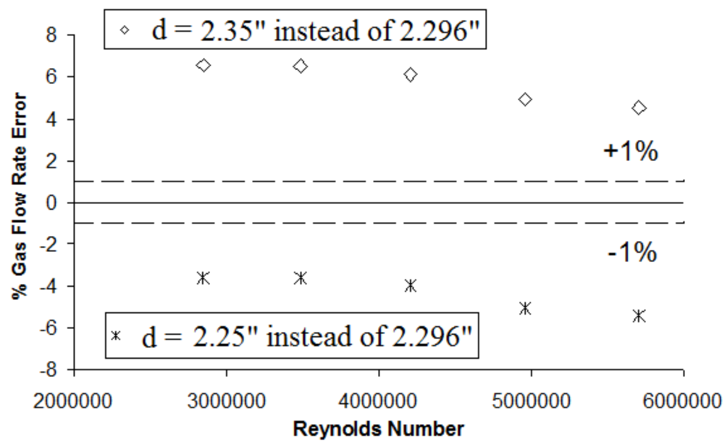

Figure 13. Venturi meter errors associated with incorrect throat diameter inputs.

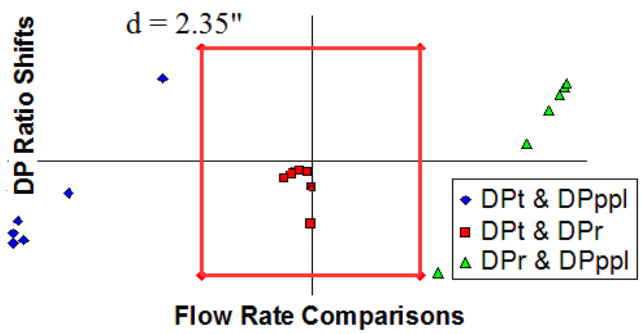

Figure 14. Diagnostic result for a positive throat diameter and flow rate prediction error.

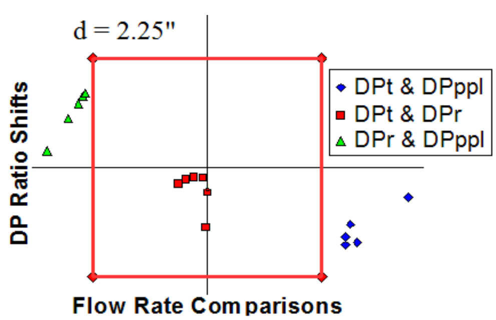

Figure 15. Diagnostic result for a negative throat diameter and flow rate prediction error.

It is clear from the examples that the diagnostic system is somewhat more sensitive to inlet diameter errors than throat diameter errors. It takes a *relatively* larger error in throat diameter than inlet diameter to trigger a warning (i.e. get points outside the NDB). Also note that the positive and negative errors in the throat diameters produce positive and negative flow rate prediction errors respectively. The patterns on the NDB plots for positive and negative flow rate prediction errors match that shown for the inlet diameter errors. That is a positive flow rate error has a diagnostic pattern of the traditional DP to PPL pair on the negative side and the recovered DP to PPL positive side of the NDB plot. The opposite is true of the negative flow rate error.

Finally, note in the above examples the traditional and recovered DP pair is not sensitive to these types of errors. That is not to say that this DP ratio is not useful as a Venturi meter diagnostic. Different Venturi meter problems are identified by different DP pairs. The next example shows a scenario where the recovered DP and PPL pair is an inactive diagnostic check while the traditional and recovered DP pair actively signals the problem.

5.3. <u>**Incorrect Inputs of Discharge Coefficient**</u>

As most Venturi meters built for natural gas flows require calibration the unique discharge coefficient needs to be keypad entered into the flow computer along with the inlet and throat diameters. Mistakes can be made here. Here the Venturi meter was calibrated to have a discharge coefficient of 1.003. Therefore, the first example considers the obviously typing error where 1.03 is entered to the flow computer. This induces a positive bias on the flow meters flow rate prediction of approximately 2.7%. Whereas a correctly operating meter will give the flow rate prediction in a range of +1% to -1% this incorrect throat diameter has shifted this range to +3.7% to +1.7%.

The second example simply considers the opposite effect, i.e. a discharge coefficient input of 0.97. This induces a negative bias on the flow meters flow rate prediction of approximately 2.7%. Whereas a correctly operating meter will give the flow rate prediction in a range of +1% to -1% this incorrect throat diameter has shifted this range to -1.7% to -3.7%. These errors are shown in Figure 16. Figure 17 shows the diagnostic result of the positive discharge coefficient and flow rate error. Figure 18 shows the diagnostic result of the negative discharge coefficient and flow rate error. The diagnostics pick up that the meter flow rate prediction error. Note that while inlet and throat diameter input errors are not seen by the traditional and recovered DP pair, here for the case of the discharge coefficient error diagnostics it is the most sensitive of the three DP pairs.

This was one example of the diagnostic system indicating a problem due to an erroneous discharge coefficient input. The diagnostic system is likewise sensitive to ***any*** error in inputs of the six calibration parameters, i.e. the discharge coefficient, expansion flow coefficient, PPL coefficient, PLR, PRR and RPR. Any significant error in any of these parameters will show a problem on the NDB plot. In fact only an error in the discharge coefficient causes an actual flow rate error. However, an indicated problem caused by any of the other five parameters should not be considered a “false alarm”. A Venturi meter system operating with such a diagnostic system is believed by its operator to have a flow rate output, with an associated uncertainty ***and*** a comprehensive diagnostic system assuring the correctness of the meter output. However, such an alarm is indicating the true fact that *something* is defective with either the traditional meter and / or the meters diagnostic system that he previously believed to be fully serviceable. So an alarm due to an input error of the expansion flow coefficient, PPL coefficient, PLR, PRR or RPR is an alarm stating a real issue with the overall Venturi meter diagnostic capable system. Furthermore, if the operator has been lax enough to input at least one wrong parameter then the resulting warning is stating it is good practice to double check ***all*** inputs again.

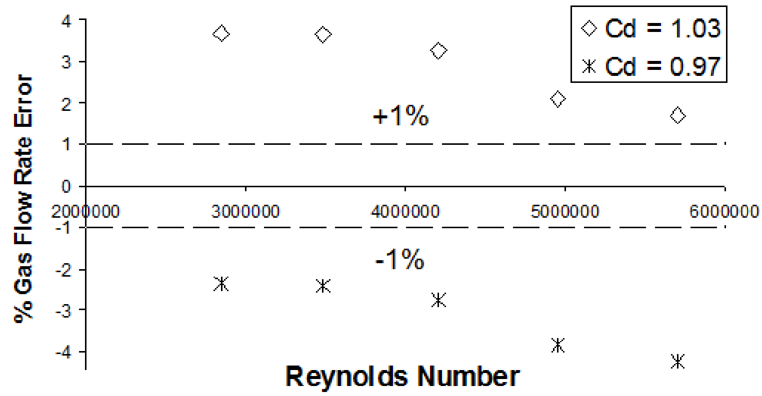

Figure 16. Venturi meter errors associated with incorrect throat diameter inputs.

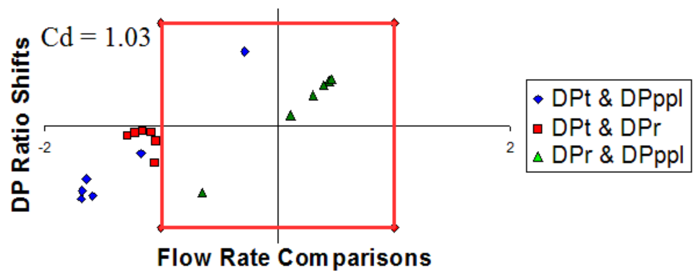

Figure 17. Diagnostic result for a positive discharge coefficient & flow rate error.

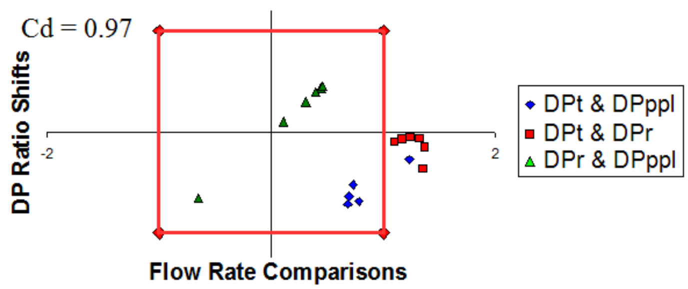

Figure 18. Diagnostic result for a negative discharge coefficient & flow rate error.

5.4. **A Saturated DP Transmitter**

Any given Venturi meter application has a DP transmitter spanned to read that expected DP range. If in practice the real DP produced exceeds the maximum DP value of the span the transmitter is said to be "saturated". A saturated DP transmitter sends to the flow computer the spanned DP value and not the actual higher DP. This is a common source of error with Venturi meters.

In this example the data point which produced 13,199 Pa (i.e. 53.1 "WC) is considered. If we had spanned the DP transmitter to 50"WC (i.e. 12,432 Pa) then the calculation would have received this lower DP and a negative flow rate prediction error of approximately 2.5% would have been produced. Traditionally there is no way for a Venturi meter system to self-diagnose such an issue. In this example the traditional DP and the PPL are being directly read. That is there are two DP transmitters installed with the Venturi meter. The third DP, the recovered DP is found by equation 1. (In this particular example we also assume that the PPL transmitter is not saturated – although if it was the diagnostics would still successfully show a problem exists.) Figure 19 shows the diagnostic result of such a situation. Hence, the diagnostics have seen that a problem exists.

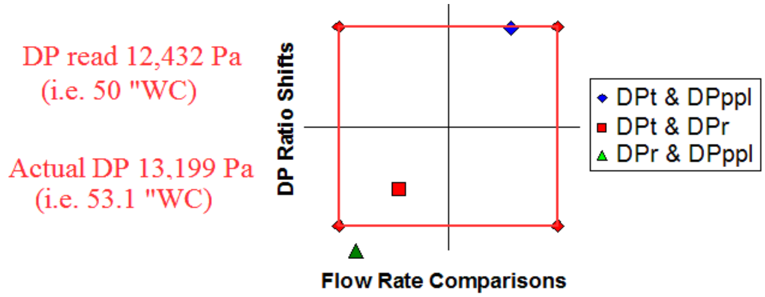

Figure 19. Saturated DP transmitter diagnostic result for two DP transmitters in use.

Note that it is interesting to observe in Figure 19 that it is the relationship of the recovered DP and PPL that shows the problem. This is initially surprising as the source of the problem is the ***other*** DP, i.e. the traditional DP. The reason the recovered DP and PPL pairing show the problem is because the recovered DP is derived from the erroneously read traditional DP (and is therefore also in error) and that the relationship of the recovered DP and PPL is a diagnostic check particularly sensitive to Venturi meter DP reading errors. The traditional DP to PPL pair diagnostic method does not have enough sensitivity to clearly see this particular problem. (That is, it would take a larger discrepancy in the actual to read traditional DP for the traditional DP to PPL to see this problem.)

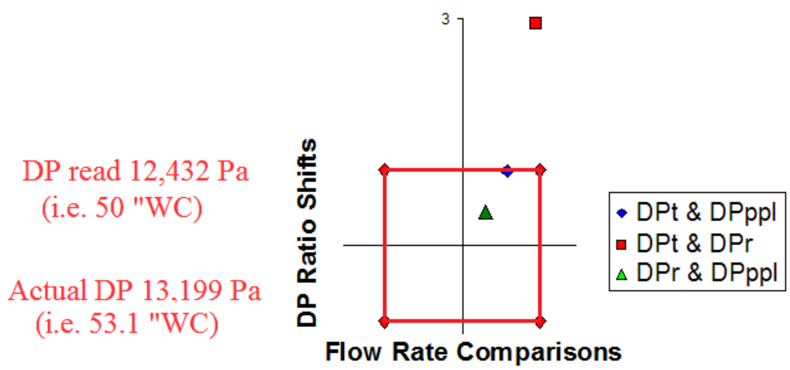

Figure 19a. A saturated DP transmitter diagnostic result for three DP transmitters in use.

If the Venturi meter operator chose to operate with three DP transmitters, thereby reading each DP directly, a different diagnostic result occurs for this particular traditional DP transmitter saturation example. The diagnostic results of this scenario are shown in Figure 19a. In this case, the recovered DP and PPL pair are both read correctly and show no problem. However, the other two DP pairs have the error with the traditional DP transmitter. Again the traditional DP to PPL pair diagnostic method does not have enough sensitivity to see this problem (not surprisingly as it's the same result as above) but the traditional to recovered DP pair clearly shows a significant problem. Here it is clear that when using three DP transmitters the traditional to recovered DP pair diagnostic check is more sensitive to the problem than the recovered DP to PPL pair diagnostic check for the case of only using two DP transmitters. Therefore, the extra effort and expense of a third DP transmitter can be offset by the increased sensitivity of the resulting diagnostic system.

This was one example of the diagnostic system indicating a problem due to an erroneous DP reading. The diagnostic system is likewise sensitive to ***any*** DP reading problem, such as drifting transmitters, incorrectly calibrated transmitters, blocked impulse lines etc.

5.5. **Wet Gas Flow**

Venturi meters are often procured for use with a gas flow. However, in industry flows which are assumed to be single phase gas flows can actually be wet gas flows. Common examples of this are saturated steam flows (where the steam quality is less than 100%) or natural gas flows where the gas has some entrained light oils and water.

In this example 0.62 kg/s of a light hydrocarbon liquid (kerosene) is entrained with the natural gas flow of 6.05 kg/s. The pressure is 56.1 Bar, the temperature 304K and the gas density is 43.2 kg/m3. This is a liquid to gas mass flow ratio of 0.102 (i.e. a GVF of 99.4%, i.e. a Lockhart Martinelli parameter of 0.024). The liquids presence affects the traditional DP being produced. The resulting uncorrected gas flow rate prediction from the Venturi meter has an 8.6% liquid induced error.

The Venturi meters diagnostic response to this wet gas flow condition is shown in Figure 20. Clearly, the diagnostics have seen that the meter has a problem. The liquids presence had a great effect on the Venturi meters performance. The liquid to gas mass flow ratio was not particularly high compared to many actual wet gas flow conditions found in the natural gas production industry. However, the meter had an 8.6% positive bias (or "over-reading") and the diagnostic check had a dramatic result showing the system was very far from operating according to the standard single phase flow response.

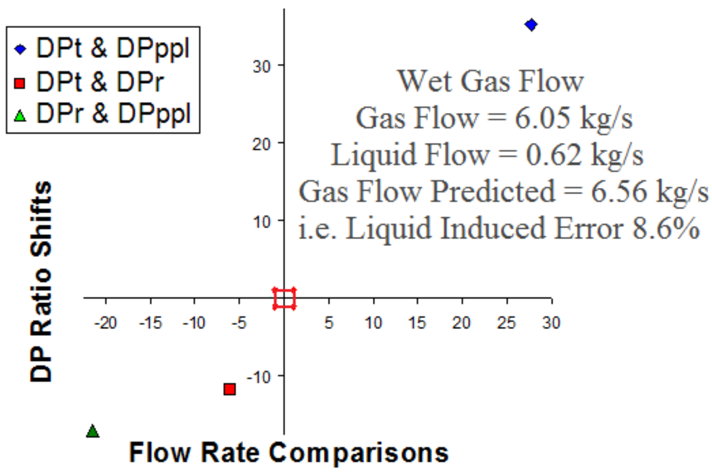

Figure 20. Sample relatively low liquid loading wet gas flow diagnostic result.

6. **Conclusions**

These patent pending diagnostic methods for Venturi meters are simple but *very* effective and of great practical use for monitoring a Venturi meter under assumed single phase flow metering applications. Furthermore, the proposed method of plotting the Venturi meter diagnostic results on a graph with a NDB aids the meter user in this task. The diagnostics and NDB presentation are capable of detecting *most* real world problems that affect the flow rate prediction. However, it should be noted that this system can not (yet at least) tell the operator what the particular problem is or what the resulting gas flow rate prediction error is. Nevertheless, as there is currently no accepted Venturi meter diagnostics that can even indicate that some unspecified error exists, this is in the authors view, a significant advance in Venturi flow meter capability.

One finding was that different problems causing the same absolute errors on the traditional meter flow rate prediction can have significantly different sensitivities to the diagnostics. For example for this data set a 3% flow metering error due to a throat inlet area is just noticeable by the diagnostics. However a wet gas 3% error is very noticeable by the diagnostics. Therefore, if *in the long run* the diagnostic system is to be developed to attempt predict absolute errors it will first be necessary to isolate the particular problem causing the warning. Then, and only then, with that particular problems known diagnostic sensitivity may it be possible to attempt to quantify a metering error.
It is strongly suspected that as more experience and knowledge is built up regarding the diagnostic plots particular patterns will become known as signals of particular problems. For example, note that in the cases of the incorrect inlet diameter, throat diameters or the incorrect discharge coefficient that the meter flow rate comparison diagnostic check alone notes the problem. The DP ratio diagnostic check sees no problem. Now note that for the case of the saturated DP transmitter the DP ratio diagnostic checks indicate the problem (and the flow rate comparison diagnostics may indicate a problem depending on the scale of this particular type of error). We also see that the wet gas flow causes both the flow rate comparison and DP ratio diagnostic checks to indicate a problem. So certain diagnostic plot patterns showing a metering problem can only be created by certain groups of problems. Furthermore, developing understanding and experience can further break down these general groups to smaller sub-groups. For example in the cases of incorrect inlet and throat diameters (where the flow rate comparison check alone signals a problem) we see one of the three checks is immune to these problems while the other two diagnostic points have opposite x-axis signs. On the other hand when we have a discharge coefficient error (where the flow rate comparison check alone signals a problem) we see one of the three checks is immune but both of the other points have the same x-axis signs. This then distinguishes the diagnostic plots for the discharge coefficient problem and an inlet or throat diameter problem. Another example is that wet gas flow has a significant effect on all the flow comparison and DP ratio diagnostic checks. A major divergence from the NDB with a plot of the traditional DP and PPL pair in the first quadrant and the other two points in the third quadrant strongly suggests a wet gas flow issue. Therefore it is considered likely that a lot of valuable information is contained in the diagnostic plots beyond the simple alert that the meter has some unspecified problem. Further development and experience will certainly produce significantly more detailed diagnostics from this simple concept.

Finally note that the data set used here was not recorded for this research and development. It was recorded by CEESI on the wet gas flow facility. The subsequent dry gas data used does not therefore have the same low uncertainty as would be attained using the gas calibration facilities. Such lowered uncertainties on the full calibration of the meter would of course improve the sensitivity of such a system to smaller flow metering problems. The author thanks CEESI for use of the data set.

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